LANSCE DIVISION TECHNOLOGY REVIEW

FIGARO—A Fast Neutron-Induced Gamma-Ray Observer

R.C. Haight, L. Zanini, M. Devlin, J.M. O'Donnell (LANSCE Division), A. Aprahamian (University of Notre Dame), J. X. Saladin (University of Pittsburgh)

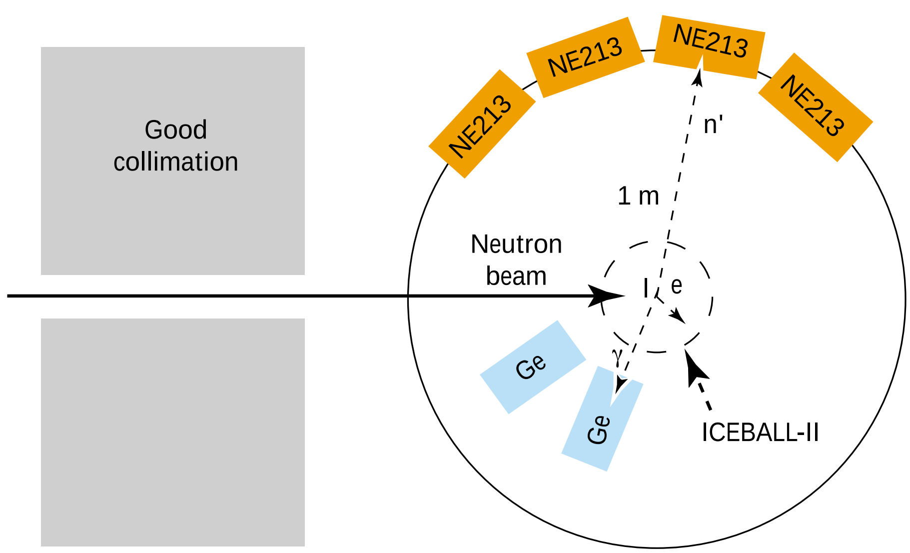
Understanding nuclear reactions is key to reliable calculations of nuclear weapons, transmutation of radioactive waste from power reactors, and synthesis of the elements in stars. These calculations depend on accurate input parameters (generally more than twenty), some of which are known fairly well, but others are uncertain by uncomfortably large amounts. Progress in narrowing down the range of possible parameters depends on new types of experimental data chosen judiciously to provide the necessary understanding. We have constructed the new Fast Neutron-Induced Gamma-Ray Observer (FIGARO) flight path at the Weapons Neutron Research (WNR) Facility to address many of these new types of measurements.

Pursuing Physics Research with FIGARO

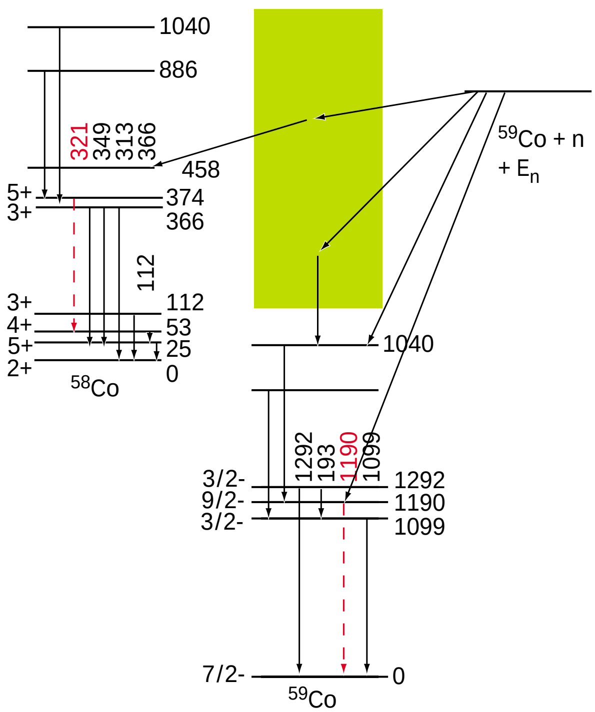
Following the great successes of GEANIE—a large array of high-resolution gamma-ray detectors—FIGARO is designed for high-resolution detection of gamma rays from neutron-induced interactions with selected target nuclei. The FIGARO layout is shown schematically in Fig. 1. Although FIGARO has fewer gamma-ray detectors than GEANIE, it offers other features, including

- extremely good collimation of the neutron beam for background reduction;
- a flexible experimental area to optimize detection efficiency and to allow for the evaluation of other detectors, such as ICEBALL (see below);
- inclusion of neutron detectors for the study of neutron-gamma coincidences (see below);
- beam time to relieve the scheduling pressure on GEANIE, which is oversubscribed; and
- a PC-based data-acquisition system.

The experimental approach with FIGARO is very similar to that of GEANIE. A pulse of neutrons, containing a wide range of neutron energies, is produced in the Target-4 spallation neutron source at WNR by the interaction of the 800-MeV proton beam from the LANSCE accelerator with a tungsten target. The neutrons, collimated to a beam of 1 to 2 cm in diameter, impinge on a sample 20 m from the source, where nuclear excitations take place. The excited nuclei decay by the emission of gamma rays, which are detected by high-resolution gamma-ray detectors near the sample. The time of flight



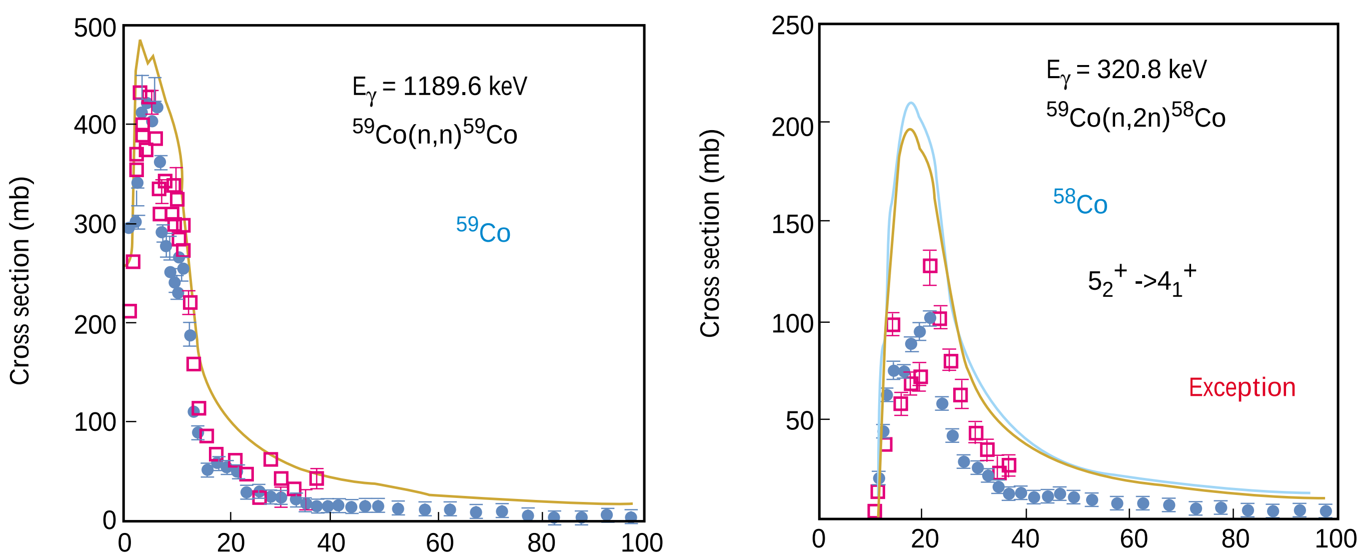
▲ ***Fig. 1.*** *Schematic layout of FIGARO showing high-resolution gamma-ray detectors, neutron detectors, and, for a different set of measurements, an internal conversion electron spectrometer array known as ICEBALL-II.*



▲ ***Fig. 2.*** *An example of excitation of nuclear states by neutron-induced reactions. The initial nucleus is ^{59}Co (the only stable isotope of cobalt), which forms a compound system when a neutron of energy (E_n) interacts with it. Excited states of ^{59}Co can be created by evaporation of one neutron. States of ^{58}Co can be formed by the evaporation of two neutrons. States of other nuclei (not shown), such as ^{59}Fe, can be formed by other reactions, for example, ^{59}Co(n,p)^{59}Fe. Only a few of the many known levels of ^{58}Co and ^{59}Co are shown for simplicity. The continuous green region in ^{59}Co denotes that there are many states at these excitation energies, and most cannot be resolved.*

(TOF) of the neutrons to the sample indicates the energy of the neutron that initiated the reaction. The gamma-ray energy indicates the particular level excited (Fig. 2). Because the neutron pulses occur 35,000 times per second, we can accumulate many events to indicate the probability (cross section) of producing particular gamma rays as a function of neutron energy (Fig. 3).

Our first measurements were on neutron interactions with ^{59}Co, where we had previously studied ^{59}Co(n,p) and ^{59}Co(n,α) reactions by detecting the emitted protons and alpha particles. Thus we already had an excellent beginning in studying at least some of the interaction possibilities. We wished to put the nuclear-reaction model calculations to more stringent tests, which can be done by measuring the gamma rays produced in the various reactions. Because we already know the quantum numbers (spins and parities) of the residual states, a comparison of the measured cross sections with calculations will tell us if angular momentum is being well handled by the calculations. For many of the gamma rays we see, the calculation does very well; an example is given in Fig. 3(a). For a few others, however, such as the example given in Fig. 3(b), the agreement is not so good. We are continuing to investigate whether the discrepant cases



▲ ***Fig. 3.*** *Cross sections for creating (a) the 1189.6-keV gamma ray in ^{59}Co via inelastic scattering and (b) the 320.8-keV gamma ray in ^{58}Co from the ^{59}Co(n,2n)^{58}Co reaction as a function of incident neutron energy. The specific transitions are given in red in Fig. 2. Recent data from FIGARO are shown as the solid circles. Previous, unpublished data from Oak Ridge National Laboratory[1] are shown as the open squares. The solid curves are predictions from the Los Alamos nuclear-reaction-model code GNASH.*

are due to insufficient knowledge of the levels or to some more general problem with the reaction theory.

Soon we will add neutron detection to FIGARO. The neutron detectors will be located approximately 1 m from the sample so that the TOF measurements of the emitted neutron (the " n' " in Fig. 1) can be obtained and its energy deduced. By knowing the energies of both the incident and emitted neutron energies in an (n,n') excitation, we can ascertain the excitation energy of the nucleus. We will investigate questions such as "how does the yield of a particular gamma ray then depend on this excitation energy?" Modern theories say that certain excitation energies of the nuclei emphasize certain angular momenta more than others, and the distribution of angular momenta should be reflected in the gamma-ray decay of low-lying levels, where we know the angular momenta.

Studying cobalt, where the nuclear structure and some reactions are well known, allows us to focus on more stringent tests of nuclear-reaction models. We also invoke information from nearby nuclei, such as ^{58}Ni and ^{60}Ni, where we have studied the (n,p) and (n,α) reactions. Those comparisons have led us further into studying the gamma rays from neutron-induced excitation of these nickel isotopes—measurements that were recently completed with FIGARO. Cobalt and nickel are two important structural materials in many types of nuclear-energy schemes (fission and fusion energy, for example), and so the information that we obtain has a direct connection to applications.

Yet another application of FIGARO is that of reactions on long-lived radioactive isotopes. A major goal of the AAA program is the incineration of long-lived radioactive isotopes produced as fission products in nuclear power reactors. Neutron interactions with these isotopes can transmute them into isotopes that are stable or very short-lived, so that they decay much faster. One of the major fission products is ^{99}Tc, which has a half-life of 230,000 yr. We were able to obtain a sample of 50 g of this isotope and measure the gamma rays produced by neutron interactions with FIGARO. We will be comparing our results with nuclear model calculations to deduce relevant destruction cross sections, such as ^{99}Tc(n,α)^{96}Nb, ^{99}Tc(n,2n)^{98}Tc, and ^{99}Tc(n,3n)^{97}Tc.

Commissioning of FIGARO Helped Assess ICEBALL-II Capabilities

During the commissioning phase of FIGARO, we had the opportunity to assess the capabilities of another type of detector, ICEBALL-II, from the University of Pittsburgh. This instrument detects internal conversion electrons (ICEs), which are analogous to gamma rays. With this process, instead of a transition between two levels taking place by gamma-ray emission, the energy is given to one of the atomic electrons. The probability of an ICE versus gamma-ray emission depends on the transition energy (ICE wins at lower transition energies), the angular-momentum difference (ICE wins for larger multipolarities and for monopole transitions), and the atomic number of the nucleus (ICE does better for higher atomic numbers). We were especially interested in monopole transitions in ^{238}U, where there is no change in angular momentum and where the ICE process is the only possible mode of decay. These transitions have never been seen before in ^{238}U, and they could be relevant to GEANIE experiments that involve nuclear reactions on uranium and plutonium isotopes. We therefore excited ^{238}U with neutrons at the FIGARO beam line. Although we did not observe the ICE lines we sought, we were able to set an upper limit on the probability that these lines were produced.

In summary, we have constructed the FIGARO flight path and have made initial measurements on ^{59}Co(n,xγ) reactions, ^{58,60}Ni(n,xγ) reactions, ^{99}Tc(n,xγ) reactions, and ^{238}U(n,conversion electron) reactions. The flight path works very well, and a new PC-based data-acquisition system has provided increased reliability and utility. The addition of further detectors will allow neutron/gamma-ray coincidence measurements to put further constraints on nuclear-reaction theories.

References

1. T. E. Slusarchyk, "Preliminary Cross Sections for Gamma Rays Produced by Interaction of 1- to 40-MeV Neutrons with ^{59}Co," Oak Ridge National Laboratory report ORNL/TM-11404 (1989).

For more information, contact Robert Haight (LANSCE-3), 505-667-2829, MS H855, haight_robert_c@lanl.gov.

Produced by the LANSCE-4 communications team: Sue Harper, Grace Hollen, Barbara Maes, Sharon Mikkelson and Garth Tietjen.

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